

Bounds on anomalous $\gamma\gamma H$ and $Z\gamma H$ couplings at future $e\gamma$ linear colliders

E. Gabrielli ^{1 a}, V.A. Ilyin ² and B. Mele ³.

¹ Departamento de Física Teórica, Universidad Autónoma, Madrid, Spain

² Institute of Nuclear Physics, Moscow State University, Russia

³ Physics Department, Roma University 1, and INFN Roma1, Italy

Abstract

We study the bounds on the anomalous contributions to the $\gamma\gamma H$ and $Z\gamma H$ vertices that can be obtained via the process $e\gamma \rightarrow eH$. We consider the representative cases of an intermediate Higgs mass production of $m_H = 120$ GeV and for a center of mass energy of $\sqrt{s} = 500$ GeV and $\sqrt{s} = 1500$ GeV. We use a model independent analysis based on $SU(2) \times U(1)$ invariant operators of $dim = 6$ added to the Standard Model lagrangian. We find that this process provides an excelent way to put strong constraints both in the sector of CP-even and CP-odd anomalous couplings contribution to the $\gamma\gamma H$ and $Z\gamma H$ vertices.

1 Introduction

The Higgs boson sector is a crucial part of the Standard Model (SM) still escaping direct experimental verification. Once the scalar boson will be discovered either at LEP2, upgraded TEVATRON or at LHC, testing its properties will be a central issue at future linear colliders. In particular, an e^+e^- collider with centre-of-mass (c.m.) energy $\sqrt{s} \simeq (300 \div 2000)\text{GeV}$ and integrated luminosity $\mathcal{O}(100) \text{ fb}^{-1}$ will allow an accurate determination of the mass, some couplings and parity properties of this new boson ^{1,2}. Among other couplings, the interaction of scalars with the neutral electroweak gauge bosons, γ and Z , are particularly interesting. Indeed, one can hope to test here some delicate feature of the Standard Model — the relation between the spontaneous symmetry breaking mechanism and the electroweak mixing of the two gauge groups $SU(2)$ and $U(1)$. In this respect, three vertices could be measured — ZZH , $\gamma\gamma H$ and $Z\gamma H$. While the ZZH vertex stands in SM at the tree level, the other two contribute only at one-loop. This means that the $\gamma\gamma H$ and $Z\gamma H$ couplings could be sensitive to the contributions of new particles circulating in the loop.

Here, we discuss the case of an intermediate-mass Higgs boson, that is with $M_Z \lesssim m_H \lesssim 140$ GeV. A measurement of the $\gamma\gamma H$ coupling should be possible by the determination of the BR for the decay $H \rightarrow \gamma\gamma$, e.g. in the LHC Higgs discovery channel, $gg \rightarrow H \rightarrow \gamma\gamma$. Furthermore, at future photon-photon colliders^b,

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^bTwo further options are presently considered for a high-energy e^+e^- linear collider, where one or both the initial e^+/e^- beams are replaced by photon beams induced by Compton backscattering of laser light on the high-energy electron beams ³. Then, the initial real photons could be to a good degree monochromatic, and have energy and luminosity comparable to the ones of the parent electron beam ⁴.

the precise measurement of the $\gamma\gamma H$ vertex looks realistic at the resonant production of the Higgs particle, $\gamma\gamma \rightarrow H$. To this end, the capability of tuning the $\gamma\gamma$ c.m. energy on the Higgs mass, through a good degree of the photons monochromaticity, will be crucial for not diluting too much the $\gamma\gamma \rightarrow H$ resonant cross section over the c.m. energy spectrum. Measuring the $Z\gamma H$ vertex is in general more complicated. Indeed, if one discusses the corresponding Higgs decay, the final states include the Z decay products, jets or lepton pairs, where much heavier backgrounds are expected. Then, one can discuss the $H \rightarrow \gamma Z$ decay only for $m_H \gtrsim 115$ GeV (and $m_H \lesssim 140$), when the corresponding branching is as large as $\mathcal{O}(10^{-3})$.

Another possibility of measuring the $Z\gamma H$ vertex is given by collision processes. At electron-positron colliders, the corresponding channels are $e^+e^- \rightarrow \gamma H$ and $e^+e^- \rightarrow ZH$. However, in the ZH channel the $Z\gamma H$ vertex contributes to the corresponding one-loop corrections, thus implying a large tree level background. The reaction $e^+e^- \rightarrow \gamma H$ has been extensively studied in the literature^{5,6,7}. Unfortunately, the $e^+e^- \rightarrow H\gamma$ channel suffers from small rates, which are further depleted at large energies by the $1/s$ behavior of the dominant s-channel diagrams. For example, $\sigma_S \approx 0.05 \div 0.001$ fb at $\sqrt{s} \sim 500 \div 1500$ GeV. We estimated the main background coming from the $e^+e^- \rightarrow \gamma b\bar{b}$ process, and found it rather heavy: $\sigma_B \approx 4 \div 0.8$ fb for $m_{b\bar{b}} = 100 \div 140$ GeV, assuming a high resolution in the measurement of the invariant mass of $b\bar{b}$ quark pair, i.e. ± 3 GeV, and applying a minimum cut of 18° on the angles $[\gamma - beams]$ and $[b(\bar{b}) - beams]$. Then, at $\sqrt{s} = 1.5$ TeV, we get $\sigma_B \approx 0.4 \div 0.07$ fb. One can conclude that measuring the $Z\gamma H$ vertex is not an easy task.

Recently, the Higgs production in electron-photon collisions through the one-loop process $e\gamma \rightarrow eH$ was analysed in details⁸. This channel will turn out to be an excellent tool to test both the $\gamma\gamma H$ and $Z\gamma H$ one-loop couplings with high statistics, without requiring a fine tuning of the c.m. energy.

In this paper we analyse the prospects of the $e\gamma \rightarrow eH$ reaction in setting experimental bounds on the value of the anomalous $\gamma\gamma H$ and $Z\gamma H$ couplings⁹. For this analysis we use a model independent approach, where $dim = 6$ $SU(2) \times U(1)$ invariant operators are added to the SM Lagrangian. In realistic models extending the SM, these operators contribute in some definite combinations. However, if one discusses the bounds on the possible deviations from the standard-model one-loop Higgs vertices, this approach can give some general insight into the problem. These anomalous operators contribute to all the three vertices $\gamma\gamma H$, $Z\gamma H$ and ZZH , with only the first two involved in the $e\gamma \rightarrow eH$ reaction. Even though the anomalous contributions to the $\gamma\gamma H$ vertex can be bounded through the resonant $\gamma\gamma \rightarrow H$ reaction, competitive bounds can be obtained by measuring the total rate of the discussed reaction, $e\gamma \rightarrow eH$.

The paper is organized as follows: in the next section we present the $e\gamma \rightarrow eH$ process and outline its main features. In section 3 we present the $dim = 6$ operators which induces the anomalous vertices contributions to the $e\gamma \rightarrow eH$ amplitude. Section 4 contains the numerical results for the bounds on the anomalous couplings and the conclusions.

2 The reaction $e\gamma \rightarrow eH$ in the SM: main features

In⁸, we presented the complete analytical results for the helicity amplitudes of the $e\gamma \rightarrow eH$ process in the SM (see also reference¹⁰). This amplitude is given by the diagrams contribution denoted as ‘ $\gamma\gamma H$ ’ and ‘ $Z\gamma H$ ’, which are related to the $\gamma\gamma H$ and $Z\gamma H$ vertices respectively, and a ‘BOX’ contribution. The separation of the rate into these three parts corresponds to the case where the Slavnov-Taylor identities for the ‘ $\gamma\gamma H$ ’ and ‘ $Z\gamma H$ ’ Green functions just imply the transversality with respect to the incoming photon momentum.

The total rate of this reaction is rather high, in particular for m_H up to about 400 GeV, one finds $\sigma > 1$ fb. If no kinematical cuts are imposed then the main contribution to the cross section is given by the $\gamma\gamma H$ vertex; this is due to the t-channel photon propagator given by the $\gamma\gamma H$ vertex. On the contrary the $Z\gamma H$ vertex contribution is depleted by the Z propagator.

Nevertheless, as discussed in⁸, the $Z\gamma H$ vertex effects can be extracted from $e\gamma \rightarrow eH$ by implementing a suitable strategy to reduce the $\gamma\gamma H$ vertex contribution: this requires a final electron tagged at large angle together with a transverse momentum cut $p_T^e > 100$ GeV. For example, for $p_T^e > 100$ GeV, we found that $Z\gamma H$ is about 60% of $\gamma\gamma H$, and $Z\gamma H$ gives a considerable fraction of the total production rate, which is still sufficient to guarantee investigation (about 0.7 fb).

The main irreducible background to the process $e\gamma \rightarrow eH \rightarrow e b \bar{b}$ comes from the channel $e\gamma \rightarrow e b \bar{b}$. A further source of background is the charm production through $e\gamma \rightarrow e c \bar{c}$, when the c quarks are misidentified into b ’s. We also assume a 10% probability of misidentifying a c quark into a b . The cut $\theta_{b(c)-beam} > 18^\circ$ (between each $b(c)$ quark and both the beams reduces the signal and background at a comparable level. Numerically the $e\gamma \rightarrow e c \bar{c}$ “effective rate” is of the same order as the $e\gamma \rightarrow e b \bar{b}$ rate. A further background, considered in⁸, is the resolved $e\gamma(g) \rightarrow e b \bar{b}(e c \bar{c})$ production, where the photon interacts via its gluonic content. This background was found negligible.

Important improvements in the S/B ratio can be obtained by exploiting the final-electron angular asymmetry in the signal. Indeed, the final electron in $e\gamma \rightarrow eH$ moves mostly in the forward direction.

The main conclusion obtained in⁸ is the following: with a luminosity of 100 fb^{-1} , at $\sqrt{s} = 500 \text{ GeV}$, one expects an accuracy as good as about 10% on the measurement of the $Z\gamma H$ effects assuming the validity of Standard Model. Therefore we can use the suitable strategy used in⁸ to study the sensitivity of the $e\gamma \rightarrow eH$ process to the anomalous coupling contributions in both the $\gamma\gamma H$ and $Z\gamma H$ vertices.

3 Anomalous vertices

Now we consider the possibility that the new physics affects the bosonic sector of the SM through low energy effective operators of $\dim = 6$. These operators contribute to the $e\gamma \rightarrow eH$ amplitude via anomalous couplings to the $\gamma\gamma H$ and $Z\gamma H$ vertices.

In particular there are two pairs of $\dim = 6$ operators^c, CP-even and CP-odd

^cWe assume that $SU(2) \times U(1)$ local gauge invariance of the Standard Model should be valid

respectively, giving anomalous contributions to the process $e\gamma \rightarrow eH$:

$$\mathcal{L}^{eff} = d \cdot \mathcal{O}_{UW} + d_B \cdot \mathcal{O}_{UB} + \bar{d} \cdot \bar{\mathcal{O}}_{UW} + \bar{d}_B \cdot \bar{\mathcal{O}}_{UB}, \quad (1)$$

$$\mathcal{O}_{UW} = \frac{1}{v^2} \left(|\Phi|^2 - \frac{v^2}{2} \right) \cdot W^{i\mu\nu} W_{\mu\nu}^i, \quad \mathcal{O}_{UB} = \frac{1}{v^2} \left(|\Phi|^2 - \frac{v^2}{2} \right) \cdot B^{\mu\nu} B_{\mu\nu}, \quad (2)$$

$$\bar{\mathcal{O}}_{UW} = \frac{1}{v^2} |\Phi|^2 \cdot W^{i\mu\nu} \tilde{W}_{\mu\nu}^i, \quad \bar{\mathcal{O}}_{UB} = \frac{1}{v^2} |\Phi|^2 \cdot B^{\mu\nu} \tilde{B}_{\mu\nu}, \quad (3)$$

where $\tilde{W}_{\mu\nu}^i = \epsilon_{\mu\nu\mu'\nu'} \cdot W^{i\mu'\nu'}$ and $\tilde{B}_{\mu\nu} = \epsilon_{\mu\nu\mu'\nu'} \cdot B^{\mu'\nu'}$. In these formulas Φ is the Higgs doublet and v is the electroweak vacuum expectation value.

The $\gamma\gamma H$ and $Z\gamma H$ anomalous terms contribution, in terms of $d, d_B, \bar{d}, \bar{d}_B$ couplings, to the helicity amplitudes of $e\gamma \rightarrow eH$ can be found in⁹.

4 Bounds on anomalous $\gamma\gamma H$ and $Z\gamma H$ couplings: numerical results and conclusions

In this section we analyse the numerical results⁹ for the bounds on the anomalous couplings d, d_B and \bar{d}, \bar{d}_B which are obtained from the $e\gamma \rightarrow eH$ process.^d These bounds have been computed by using the requirement that no deviation from the SM cross section is observed at the 95% CL, in particular we have:

$$N^{\text{anom}}(\kappa) < 1.96 \cdot \sqrt{N^{\text{tot}}(\kappa)}, \quad \kappa = d, d_B, \bar{d}, \bar{d}_B, \quad (4)$$

$$N^{\text{tot}}(\kappa) = \mathcal{L}_{int} \cdot [\sigma_S(\kappa) + \sigma_B], \quad N^{\text{anom}}(\kappa) = \mathcal{L}_{int} \cdot [\sigma_S(\kappa) - \sigma_S(0)]. \quad (5)$$

where \mathcal{L}_{int} is the integrated luminosity, N^{tot} and N^{anom} denote respectively the total number of observed events and the anomalous number of events deviating from the expected SM predictions for the signal. Here, by $\sigma_S(\kappa)$ we mean the cross section of the signal reaction $e\gamma \rightarrow eH \rightarrow e b \bar{b}$ with the anomalous contributions, so $\sigma_S(0)$ is the SM cross section. Then, by σ_B we denote the total cross section of the background processes $e\gamma \rightarrow e b \bar{b}$, $e\gamma \rightarrow e c \bar{c}$ (with 10% probability of misidentifying a c quark into a b quark).

The complete numerical results for the bounds on the CP-even d, d_B and CP-odd \bar{d}, \bar{d}_B anomalous couplings can be found in⁹. They are all obtained for a representative case of $m_H = 120$ GeV, and for $\sqrt{s} = 500$ GeV and $\sqrt{s} = 1500$ GeV, and for different electron beam polarizations $P_e = 0, 1, -1$, attainable with an integrated luminosity of 100 fb^{-1} and 1000 fb^{-1} respectively. In all these results we always assume that for each bound the only contribution is given by the corresponding anomalous coupling, switching-off the other three anomalous contributions.

From the results of reference⁹ we draw the following conclusions:

as well as so-called custodial symmetry of the gauge and Higgs sectors present in the Standard Model¹²

^d Most of the results presented in this work were obtained with the help of CompHEP package¹¹.

- The strongest bounds on the CP-even couplings at $\sqrt{s} = 500$ GeV are at the level of $|d| \lesssim 6 \times 10^{-4}$, obtained at $P_e = -1$, and $|d_B| \lesssim 2.5 \times 10^{-4}$ (with no cut on p_T^e), not depending on the e polarization. At $\sqrt{s} = 1500$ GeV, one has $|d| \lesssim 1.7 \times 10^{-4}$, obtained at $P_e = -1$ and $p_T^e > 100$ GeV, and $|d_B| \lesssim 1 \times 10^{-4}$ (with no cut on p_T^e), not depending on the e polarization.
- The strongest bounds on the CP-odd couplings at $\sqrt{s} = 500$ GeV are $|\bar{d}| \lesssim 3 \times 10^{-3}$ and $|\bar{d}_B| \lesssim 1 \times 10^{-3}$, which are obtained for $P_e = -1$ and $P_e = 1$, respectively. These bounds are quite insensitive to the cuts on p_T^e . At $\sqrt{s} = 1500$ GeV, one has $|\bar{d}| \lesssim 1.0 \times 10^{-3}$ for $P_e = -1$, with $p_T^e > 100$ GeV, and $|\bar{d}_B| \lesssim 3 \times 10^{-4}$, for $P_e = 1$, with $p_T^e > 100$ GeV.

Other processes have been studied in the literature that could be able to bound the parameters d , d_B , \bar{d} , \bar{d}_B at future linear colliders. In particular, the processes $e^+e^- \rightarrow HZ$ and $\gamma\gamma \rightarrow H$ have been studied for a e^+e^- collider at $\sqrt{s} = 1$ TeV and with 80 fb^{-1} by Gounaris et al. From $e^+e^- \rightarrow HZ$, they get $|d| \lesssim 5 \times 10^{-3}$, $|d_B| \lesssim 2.5 \times 10^{-3}$, $|\bar{d}| \lesssim 5 \times 10^{-3}$ and $|\bar{d}_B| \lesssim 2.5 \times 10^{-3}$ ¹³. The process $\gamma\gamma \rightarrow H$ can do a bit better and reach the values $|d| \lesssim 1 \times 10^{-3}$, $|d_B| \lesssim 3 \times 10^{-4}$, $|\bar{d}| \lesssim 4 \times 10^{-3}$ and $|\bar{d}_B| \lesssim 1.3 \times 10^{-3}$, assuming a particular photon energy spectrum¹⁴. These analysis assume a precision of the measured production rate equal to $1/\sqrt{N}$ (with N the total number of events), and neglect possible backgrounds. In order to set the comparative potential of our process with respect to these two processes in bounding the parameters d , d_B , \bar{d} , \bar{d}_B , we assumed $\sqrt{s} = 0.9$ TeV and (conservatively) a luminosity of 25 fb^{-1} in $e\gamma \rightarrow eH$. We then neglected any background, and assumed a precision equal to $1/\sqrt{N}$. In the case $P_e = 0$ and $p_T^e > 0$, we get $|d| \lesssim 5 \times 10^{-4}$, $|d_B| \lesssim 2 \times 10^{-4}$, $|\bar{d}| \lesssim 2 \times 10^{-3}$ and $|\bar{d}_B| \lesssim 8 \times 10^{-4}$.

This analysis confirms the excellent potential of the process $e\gamma \rightarrow eH$.

Following the conventions of reference¹⁵, one can convert these constraints into upper limits of the *new physics* scale Λ that can be explored through $e\gamma \rightarrow eH$ with $\sqrt{s} \simeq 1.5$ TeV and 10^3 fb^{-1} :

$$\begin{aligned}
|d| \lesssim 1.7 \times 10^{-4} &\rightarrow |f_{WW}/\Lambda^2| \lesssim 0.026 \text{ TeV}^{-2} \\
|d_B| \lesssim 1.0 \times 10^{-4} &\rightarrow |f_{BB}/\Lambda^2| \lesssim 0.015 \text{ TeV}^{-2} \\
|\bar{d}| \lesssim 1.0 \times 10^{-3} &\rightarrow |\bar{f}_{WW}/\Lambda^2| \lesssim 0.15 \text{ TeV}^{-2} \\
|\bar{d}_B| \lesssim 3.0 \times 10^{-4} &\rightarrow |\bar{f}_{WW}/\Lambda^2| \lesssim 0.046 \text{ TeV}^{-2}
\end{aligned} \tag{6}$$

For $f_i \sim 1$ one can explore energy scales up to about 6, 8, 2.6 and about 4.5 TeV, respectively. At $\sqrt{s} \simeq 500$ GeV and 10^2 fb^{-1} , the corresponding constraints on the couplings are a factor 2 or 3 weaker than above (reflecting into energy scales Λ lower by a factor 1.4 or 1.7, respectively), mainly because of the smaller integrated luminosity assumed.

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